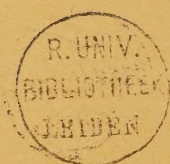


THE PHASE DIFFERENCE AND AMPLITUDE RATIO
AT THE EAR DUE TO A SOURCE OF PURE TONE

BY
F. A. FIRESTONE

• A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in the University of Michigan.

from
THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA
October, 1930, Vol. II, No. 2



THE PHASE DIFFERENCE AND AMPLITUDE RATIO
AT THE EAR DUE TO A SOURCE OF PURE TONE

BY

F. A. FIRESTONE

from

THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA

October, 1930, Vol. II, No. 2

*27699

THE PHASE DIFFERENCE AND AMPLITUDE RATIO AT THE EARS DUE TO A SOURCE OF PURE TONE

F. A. FIRESTONE
University of Michigan

ABSTRACT

Measurements of phase difference and amplitude ratio of the sound entering the ears of a man-shaped wax dummy were taken with the source at varying azimuths around the head; at 256, 1024, and 1944 cycles per second; and at distances of 20, 50, 100, and 400 cm. from the head. The measurements at the two lower frequencies agree with the values published by Hartley and Fry computed on the assumption that the head is a rigid sphere in free space, except that the observed values of amplitude ratio are about 13 percent less than the computed values on account of the interference of the neck. The observed values at 1944 cycles are quite different from the computed values.

PURPOSE

For several years past there has been considerable discussion in the literature as to how it is that with our two ears we are able to locate the angular position and approximate distance of sound sources. In an effort to collect data on this subject several experimenters, notably G. W. Stewart,* have performed series of experiments in which presumably pure tones were conducted to the ears of a subject through devices of such a nature that the amplitude ratio and phase difference of the acoustic pressures at the two ears could be varied in a known way. The subject was asked to state the direction in which the sound source appeared to be. Hartley and Fry** pointed out that in an experiment of this kind it is possible to apply to the ears many combinations of amplitude ratio and phase difference which could not possibly arise from any actual sound source in the open and that in such cases there must be a psychological adjustment of discordant data. They published a series of curves giving the amplitude ratio and phase difference at the ears for different frequencies, distances, and azimuths of a point source of pure tone, which curves were computed on the assumption that the head is a rigid sphere in free space and that the ears are properly placed holes on the surface of this sphere. On the basis of these computed curves and Stewart's data they discussed the nature of the psychological adjustments to those combinations of amplitude

* The Function of Intensity and Phase in the Binaural Location of Pure Tones. Phys. Rev. 15, May 1920, pp. 425.

** The Binaural Location of Pure Tones. Phys. Rev. 18, Dec. 1921, pp. 431.

ratio and phase difference which the computed curves showed to be impossible in actual experience.

The purpose of this investigation was to *measure* the amplitude ratio and phase difference at the ears of a man-shaped dummy when an actual source of pure tone was sounded at different azimuths and distances from it. The assumption of Hartley and Fry that the head is a rigid sphere in free space and has holes for ears is only roughly approximated in practice where one would expect an appreciable influence of reflections from the shoulders, the sound collecting effect of the external ear, and reflections from the ground.

APPARATUS

The dummy comprised a man-sized wax bust such as is used in window displays. The bust was hollow and built of a hard wax about two centimeters thick. It was fastened to a wooden box approximating the size and shape of a man's body, the whole body and shoulders being covered with one-half inch hair felt. The wax head, however, was left bare. The head had a circumference measured horizontally just above the ears of 54.5 cm., over the head and under the chin a circumference of 65.0 cm., and a diameter measured just in front of the ears of 16.4 cm. Each ear was equipped with a Baldwin earphone which was used as a microphone. Each earphone was mounted inside the head in such a manner that its diaphragm occupied approximately the position of the ear drum. A heavy brass tube of appropriate diameter served as external auditory meatus. The head was filled with coarse sand to keep the wax shell, which supported the microphones, from vibrating. As shown in Fig. 1, this dummy was mounted in a horizontal position above a flat wooden platform, 10 by 30 meters, on the roof of the building and was arranged so that it could be rotated about its horizontal axis through known angles.

The source of sound was a Baldwin loud speaker unit which was attached to a three-quarter inch pipe of proper length to resonate to the fundamental frequency, thus securing satisfactory volume and fair purity of tone. This pipe projected through the wooden platform, the end of the pipe being flush with the platform. In this manner a good approximation to a point source in free space was secured. The only disturbing reflections came from the dummy itself and from a few ventilators at a distance on the roof. The dummy was supported by a simple framework of two inch pipe near the foot. While the conditions are not exactly those of free space they are more nearly so than

is ever the case in ordinary experience; consequently, any small errors introduced on this account are not of importance.

The problem of the measurement is to determine the magnitude and phase of the voltages which are generated by the microphones due to the sound which actuates them. It might be said that the principle of the method which was used is that of an alternating current potentiometer in that the unknown voltage generated by a microphone is opposed and balanced by a voltage of known and adjustable magnitude and phase, balance being indicated by silence in headphones. The circuit is shown in Fig. 1. A vacuum tube oscillator supplies current to the source and also to the device which has been called a "phase shifter." This phase shifter consists of two approximately square coils

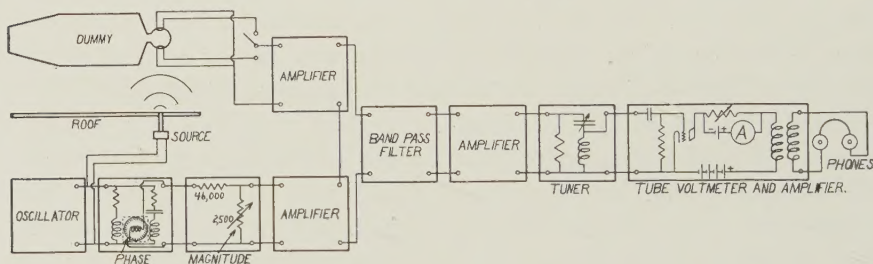


FIG. 1. Diagram of apparatus to test the reception of sound by two ears.

about 25 cm. on a side which have their planes at right angles and their centers coincident. A pickup coil about 3 cm. in diameter is mounted at the center of these coils on a shaft which lies in the line of intersection of the planes of the two coils. The two square coils are connected to the oscillator, one through a resistance of such value that the current through the coil lags the voltage of the oscillator by about 45 degrees, and the other through a resistance and condenser of such value that the current leads the voltage of the oscillator by about 45 degrees. These values are also so chosen that the currents through the two coils are approximately equal. A little reflection will show that if the magnetic fields of the two coils are at right angles in space, equal in magnitude, and 90 degrees different in phase, then the magnitude of the voltage induced in the pickup coil will be independent of its orientation about the shaft mentioned but the phase of the voltage induced in it will be changed by an Angle A when the coil is rotated through an angle A. The shaft on which the pickup coil was mounted was equipped with a dial on which the phase displacement could be

read directly in degrees. An electrostatic shield surrounded the pickup coil.

The magnitude of the voltage received from the phase shifter was controlled by a dial resistance box in series with a 46,000 ohm resistor and the pickup coil. The voltage across the dial box is approximately proportional to the resistance of the box since the current in the circuit is almost constant. Since in this experiment relative values are sufficient the settings of this box were taken as the voltages, a small computed correction being applied for the slight diminution in current in the circuit as the resistance of the box is increased. The reactance of the pickup coil was measured and found to be so small that the phase of the current in its circuit was not appreciably changed by a change in the setting of the dial resistance box.

It can thus be seen that there is one dial which controls the phase of the balancing voltage without changing the magnitude and another dial which controls the magnitude without changing the phase. The voltage from the dial resistance box goes to an amplifier whose output is in series with the output of the amplifier which receives the voltage from one of the microphones. This combined output goes to the detecting device which consists of an adjustable band pass filter which passes the fundamental and reduces the harmonics to one percent of their previous value, an amplifier, a tuned circuit which passes the fundamental and reduces any remaining harmonics another factor of one hundred, and a tube voltmeter which indicates the amount of the alternating current on meter A and amplifies it for the headphones. Although the source of sound may not be particularly pure, the filters in the detecting device insure that the readings will all be made with the fundamental only. That this result was achieved is attested by the fact that the balance was characterized by absolute silence in the headphones except for a certain amount of wind and street noises.

The phase shifter circuits were adjusted by experiment. With neither microphone connected, a certain amount of voltage was sent from the phase shifter through the detecting circuit and indicated on meter A. The resistors and condenser in series with the coils of the phase shifter were then adjusted till the meter A showed a constant voltage as the pickup coil was turned around. It was estimated that in this manner the phase shifter could be adjusted to give readings correct to one degree.

In taking observations first one microphone was connected to the amplifier and its voltage determined in magnitude and phase by ad-

justing the phase and magnitude dials till silence was achieved in the headphones. At 256 cycles the error of setting was less than one degree and a little more than one percent. At 1944 cycles the error of setting was about 5 degrees and three percent as there seemed to be an erratic time variation in the velocity of sound on the roof which would keep the phase of the sound arriving at the microphone continually shifting. A microphone placed near the source did not experience this effect, but a microphone at a distance was troubled in this way by an amount which was roughly proportional to the distance. This change in velocity was probably due to the blowing of air of uneven temperature across the roof of the building. It was present even on nights having a minimum of wind.

After the voltage generated by one microphone had been measured in magnitude and phase, the voltage of the other microphone was similarly measured. Unfortunately, these readings cannot be directly compared since the microphones are not of equal sensitivity and they also have a relative phase difference. To surmount this difficulty the following procedure was followed: If it was desired to measure the amplitude ratio and phase difference of the sounds at the ears due to a source at an azimuth of 10 degrees from the median plane the dummy was first turned till the source was 10 degrees to the right of the median plane and the two microphone voltages were measured. The dummy was then turned so that the source was 10 degrees to the left and the two voltages again measured. Assuming symmetry of the setup, it is evident that the two readings taken with the right ear microphone may be used for computing the desired amplitude ratio and phase difference since this right ear had been in one case the ear nearer the source and in the other, the farther. Similarly, the readings taken with the left ear microphone serve as an independent determination of the desired quantities. The values determined separately from the two microphones were averaged to obtain the final result.

Many precautions were taken to eliminate the errors that are usually present in measurements of this sort. The sound which actuated the microphone entered only by way of the external auditory meatus as was tested by placing a cork in the meatus and noting that the voltage generated by the microphone was reduced to one percent of its previous value. "Bone conduction" was less than one percent in amplitude. There was negligible electrical coupling between the source and the microphones, as the microphone voltage was reduced to one percent when a cork was placed in the source pipe. The input amplifiers were

checked for constancy of amplification factor with different input voltages. The nicety with which the observations fall on a smooth curve gives considerable confidence in the accuracy of the results.

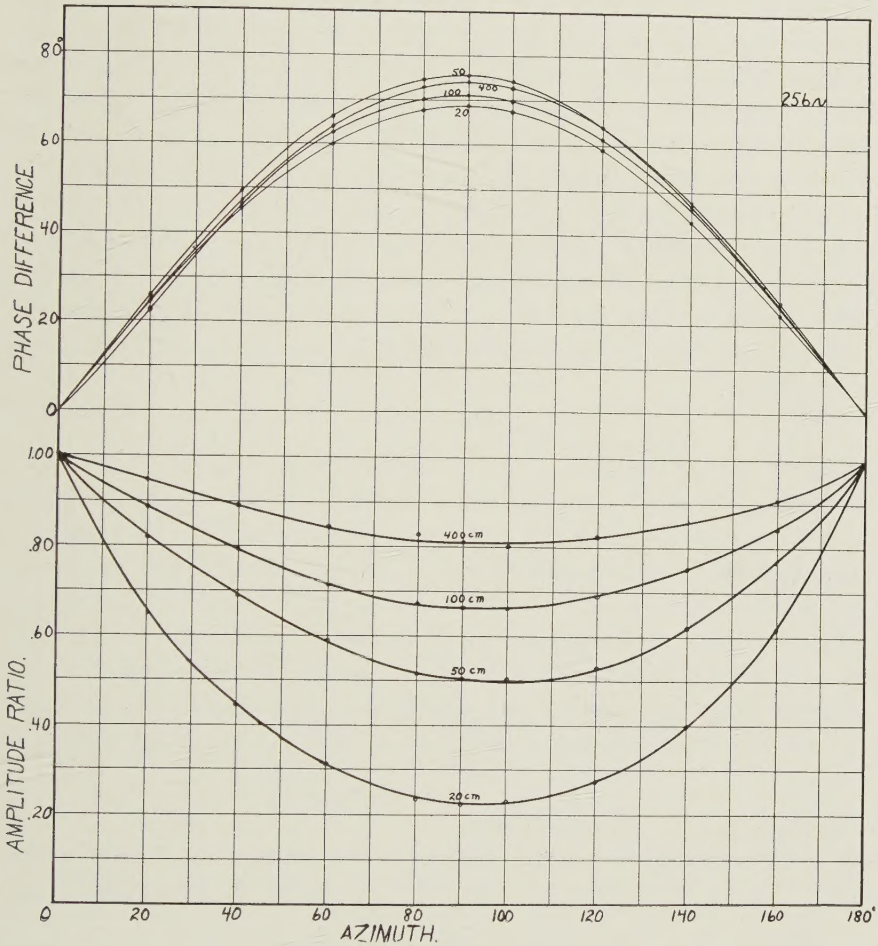


FIG. 2. Results of measurements at 256 cycles.

Observations were taken at many azimuths and four distances of the source from the center of the head, 20, 50, 100, and 400 cms. In measurements of this sort the 400 cm. distance gives results almost the same as an infinite distance since 400 cm. is fairly large compared with the diameter of the head. A complete set of measurements was taken for each of three frequencies, 256, 1024, and 1944 cycles per second. For the observations with the source at distances 100 and 400

cm. the source was flush with the roof as explained above while the dummy was supported above the source at the proper height. For the shorter distances it was felt that the repeated reflections between the dummy and the roof would cause an appreciable error when the dummy was used so close to the roof. Consequently, for the observations at distances 20 and 50 cm. the dummy was supported horizontally 400 cm above the roof and the source was supported just below the dummy at the proper distance. Under these circumstances there is an error due to reflections from the roof but since the sound amplitude is inversely proportional to the distance, the reflected sound has only 7 percent of the amplitude of the direct sound from the source at 50 cm. Furthermore, this reflected sound comes from the same side as the direct sound so that its effect on the measurements is a minimum. At the 20 cm. distance the reflected sound is only 3 percent of the direct in amplitude.

RESULTS

Fig. 2 shows the results of the measurements at 256 cycles. The curves of amplitude ratio against azimuth for different distances are very similar in shape to the computed curves given by Hartley and Fry. (Where Hartley and Fry plotted energy ratio I have chosen to plot amplitude ratio since most measuring devices give an indication proportional to the amplitude, and sound reproducing devices give pressure amplitudes proportional to their measured input). In the following table computed values interpolated from the curves of Hartley and Fry are compared with the measured values. The observed

Distance	256 cycles, azimuth 100 degree			
	Amplitude Ratio		Phase, Degrees	
	Computed	Observed	Computed	Observed
400 cm.	.90	.81	71	73
100	.76	.66	71	70
50	.57	.50	72	74
20	.28	.22	73	68

values of amplitude ratio are about 13 percent lower than the computed values, as would be expected when one considers that, in looking at the side of the head, the neck appears to be attached to about 20 percent of the circumference of the head. This obstructs the passage of a certain amount of sound to the opposite ear. While the observed and computed phases are of the same magnitude they do not agree

exactly and furthermore the observed phases do not increase regularly as the distance is decreased. This is probably due to the fact that small reflections from the shoulders and other objects are capable

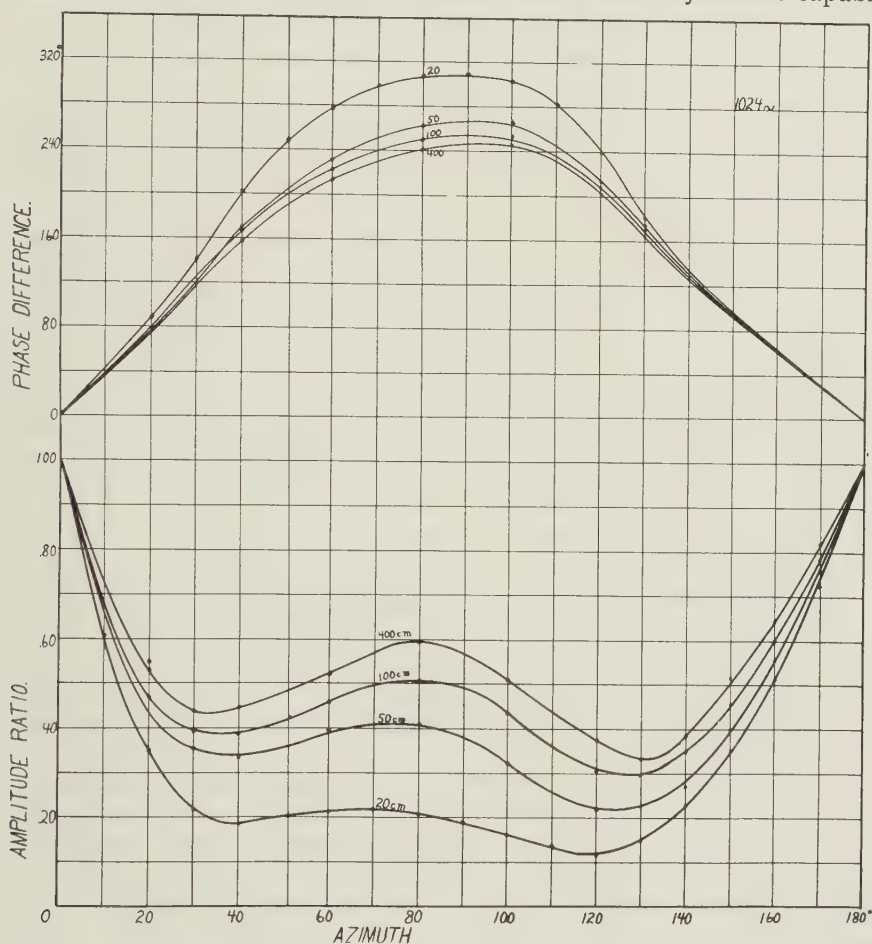


FIG. 3. Results of measurements at 1024 cycles.

of producing the few degrees of perturbation from the expected order. This makes it seem unlikely that at frequencies of 256 or less the phase difference should be capable of informing the subject as to the distance to the source, as was suggested by Hartley and Fry.* If we had here reflections from the surface of the ground as in any practical case, the confusion of the phase difference would be still worse.

* The function of Phase Difference in the Binaural Location of Pure Tones. Hartley and Fry, *Phys. Rev.* XIII, June 1919, pp. 373.

Fig. 3 shows the results of the measurements at 1024 cycles. These curves are also of the same shape as the computed curves, the hump in the center of the amplitude ratio curve being analogous to the bright spot in the center of a circular shadow. The following table gives the observed and computed values at this frequency.

Distance	1024 cycles, azimuth 80 degrees			
	Amplitude Ratio		Phase Difference, Degrees	
	Computed	Observed	Computed	Observed
400	.68	.60	262	240
100	.58	.51	267	249
50	.47	.41	269	265
20	.25	.21	277	307

Here again the observed amplitude ratios are about 13 percent lower than the computed values. The observed phase differences, while not agreeing exactly with the computed values, are now in the proper order with decreasing distance because with the shorter wave length the actual phase differences are larger and the effect of disturbing reflections is less in comparison.

The results of the measurements at 1944 cycles are shown in Fig. 4. The computed curves of Hartley and Fry at 1860 cycles are of the general shape of our Fig. 3 except that their minima are lower and closer together so that the central hump is sharper. Our observed values at this frequency disagree with the computed values in several respects. The minima near 55 and 110 degrees azimuth are much lower and sharper than the computed curves show. Presumably, these minima are caused by the destructive interference between the sound which passes around in front of the head and that which passes around the back of the head. These two sounds being very nearly equal and opposite in phase, their resultant is very small in magnitude and the phase of the resultant may vary rapidly with slight changes in the direction of the source. It was observed that near these critical azimuths the phase difference might vary as much as 360 degrees when the azimuth of the source changed by 5 degrees. On account of its erratic variations, the phase difference was not plotted in this critical range of azimuths. In addition to the expected maximum in the amplitude ratio curves at 85 degrees azimuth there is a second prominent maximum at 140 degrees which is not easy to explain. It is not mere error of observation as it appears in all four curves of Fig. 4, and all four curves were repeated a year later with the same result.

When the external ears were sawed from the dummy the maximum was still present. It is at the ear farthest from the source that the rapid variation in sound pressure with azimuth occurs, this variation being responsible for this second maximum in the amplitude ratio curve.



FIG. 4. Results measurements at 1944 cycle.

CONCLUSIONS

From these observations it is seen that near and below 1000 cycles the values of amplitude ratio and phase difference, which are computed on the assumption that the head is a rigid sphere in free space, are in good agreement with the facts, except that a better approximation can be obtained by reducing all the computed values of amplitude

ratio by about 13 percent. At frequencies as high as 2000 cycles the computed values differ from the observed values by a considerable amount. In view of the complicated relation between amplitude ratio and azimuth for a pure tone of 2000 cycles and the known fact that there is no phase effect at this frequency it is difficult to believe that such a tone could be localized.

BIBLIOGRAPHY

The Function of Intensity and Phase in the Binaural Location of Pure Tones. G. W. Stewart. Phys. Rev. 15, May 1920, pp. 425.

The Binaural Location of Pure Tones. Hartley and Fry. Phys. Rev. Dec. 1921, pp. 440.

The Function of Phase Difference in Binaural Location. Hartley. Phys. Rev. 13, pp. 373.

Binaural Computation. Stewart. Phys. Rev. 33, 1911, pp. 467.

The Intensity Sum in Binaural Location. Stewart. Phys. Rev. 2, 1913, pp. 72.

Binaural Phase Difference Computation. Stewart. Phys. Rev. 4, 1914, pp. 256.

Binaural Beats. Stewart. Phys. Rev. 1917, pp. 502 and 509.

Binaural Beats. C. E. Lane. Phys. Rev. 26, 1925, pp. 401.

Binaural Beats. Valentine. Jour. of Comparative Psychology. Oct. 1927, pp. 364.

Binaural Phase Effect and Localization of Sound. Banister. London Phil. Mag. 7-2, pp. 402 and 144.

